

Characterizing extreme fire and weather events in the Boreal Shield ecozone of Ontario

Jennifer L. Beverly^{1,*}, David L. Martell¹

*Faculty of Forestry, University of Toronto, Earth Sciences Centre,
33 Wilcocks Street, Toronto, Ont., Canada M5S 3B3*

Received 26 January 2004; received in revised form 26 January 2005; accepted 7 March 2005

Abstract

Fire frequency is the most commonly used measure to characterize fire regimes for comparisons across geographical areas or time periods. Within the boreal forest region of the Boreal Shield ecozone of Ontario, fire frequency changes over time and across longitudinal gradients have been associated with drought frequency and large-scale climate processes. While providing evidence that fire regimes differ across areas of the Boreal Shield, fire frequency alone provides little insight into the potential for extreme fire events and the extreme fire weather events that produce large and intense fires characteristic of boreal forest ecosystems. We used the statistics of extreme values to characterize dry spell extremes, or runs of consecutive days with little or no rain, and fire size extremes in east (BSE) and west (BSW) divisions of the Boreal Shield ecozone of Ontario. Extreme fire-event distributions over the 1976–1999 period were compared between two sites in the boreal forest region (i.e., Northern Coniferous and Northern Clay) and extreme dry spell event distributions for the 1963–1998 period were compared between two weather stations (i.e., Dryden and Kapuskasing). Distributions of extreme fire and dry spell events in the BSW and BSE were significantly different. Return time of a 10 000 ha fire was 5.2 years in BSW and 91.8 years BSE. Differences in dry spell extremes were consistent with fire extremes, with the return time of a 30 day dry spell event increasing from 7.5 years in the BSW to 27.8 years in the BSE.

© 2005 Elsevier B.V. All rights reserved.

Keywords: Statistics of extremes; Fire regime; Fire size; Fire weather; Natural disturbance; Drought

1. Introduction

Boreal forest ecosystems are characterized by large but infrequent high intensity crown fires (Bonan and Shugart, 1989; Johnson, 1992; Larsen, 1997; Weir et al., 2000). Fire processes in the boreal region are essential to ecosystem functioning (Heinselman, 1971), species persistence (Bergeron, 1991), and landscape diversity

(Suffling, 1990). Dominant boreal forest tree species, such as black spruce and jack pine regenerate rapidly after fire to produce a complex mosaic of even-aged patches that would not persist in the absence of large fires (Payette, 1992).

Typical boreal fires cover areas 10 000 ha in extent and routinely exceed 100 000 ha (Johnson, 1992; Attiwill, 1994). Compared with the number of small fires, large fire events in the boreal forest are relatively infrequent, but account for the majority of area burned (Stocks et al., 2002). By producing sudden changes to vast landscape areas over short time periods, individual large fires are capable of highly significant social, economic, and ecological consequences. Suppression costs alone can exceed \$1 million per day on large boreal

* Corresponding author at: Canadian Forest Service, Natural Resources Canada, Northern Forestry Centre, 5320-122 Street, Edmonton, Alta., Canada T6H 3S5. Tel.: +1 780 430 3848; fax: +1 780 435 7359.

E-mail address: jbeverly@nrcan.gc.ca (J.L. Beverly).

¹ Tel.: +1 416 978 6960; fax: +1 416 978 3834.

fires (Alberta Sustainable Resource Development, 2001) and the potential for significant negative impacts of individual large fires on timber supply, tourism, and human health that have been identified in other regions (i.e., Butry et al., 2001; Morton et al., 2003) are indicative of potential outcomes in boreal forests.

Fire processes are known to vary across longitudinal gradients in boreal Canada (Bonan and Shugart, 1989; Parisien and Sirois, 2003). Comparisons of fire processes across geographical areas typically involve estimates of fire attributes such as fire frequency, intensity, severity, extent, and season (Whelan, 1995; Reinhardt et al., 2001), of which fire frequency is the most prevalent. Boreal fire frequency has been estimated from historical fire records (i.e., Stocks et al., 2002) and through fire history studies (see review by Bergeron et al., 2004). Longitudinal variations in these estimates are particularly pronounced in east and west divisions of the Boreal Shield ecozone that divide Ontario (Fig. 1) where percent annual area burned over the 1959–1997 period calculated from the Canadian Large Fire Database (Stocks et al., 2002) was 0.6–0.8 and 0–0.2 in the west and east, respectively. Fire frequency estimated from fire history studies completed for small areas within these ecozone divisions (i.e., Suffling et al., 1982; Bergeron et al., 2001) indicated

that historical fire frequency in the BSE was less than one-third that of the BSW and current fire frequency in these areas estimated from the Canadian Large Fire Database suggest fire frequency in the BSE of Ontario is as little as one-tenth that of BSW (Bergeron et al., 2004).

Drought frequency has been identified as a factor controlling fire frequency in the eastern Boreal Shield (Bergeron and Archambault, 1993; Lefort et al., 2003; Girardin et al., 2004) and rainfall patterns associated with large-scale climate patterns are considered drivers of longitudinal variations in boreal fire frequency (Bonan and Shugart, 1989). Weather is a key influence on fire regimes (Whelan, 1995) and a primary determinant of fire incidence (Cunningham and Martell, 1973; Turner and Romme, 1994). Among conifer fuel types, weather is the most important factor influencing variation in fire behaviour and extreme fire weather results in fire behaviour that produces large and intense fires (Bessie and Johnson, 1995; Hély et al., 2001). In Canada, moisture level deficits sustained for just a few days or weeks can result in multiple ignitions of large fires (Johnson and Wowchuck, 1993; Skinner et al., 1999) and area burned is strongly influenced by long sequences of days with little or no precipitation (Flannigan and Harrington, 1988).

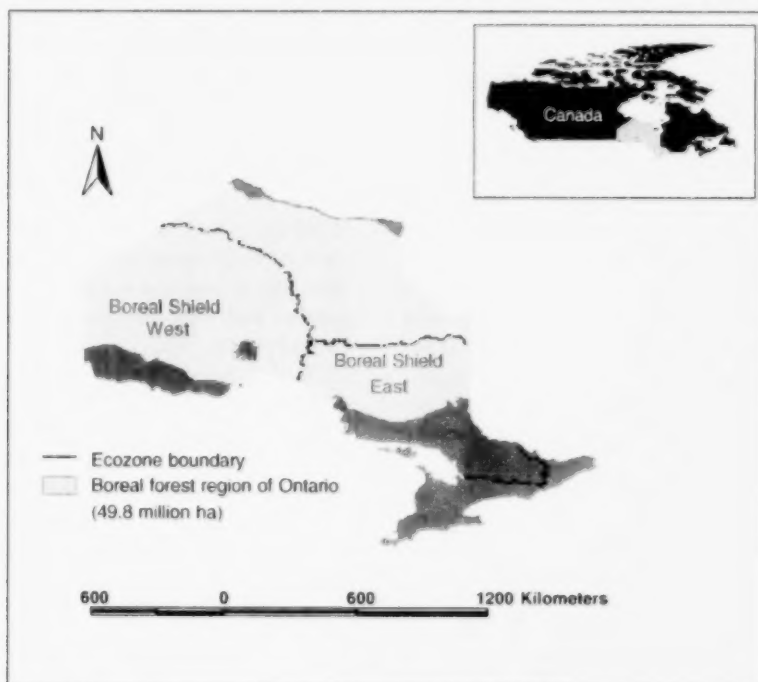


Fig. 1. Boreal forest region, and east and west divisions of the Boreal Shield ecozone, province of Ontario, Canada.

fires (Alberta Sustainable Resource Development, 2001) and the potential for significant negative impacts of individual large fires on timber supply, tourism, and human health that have been identified in other regions (i.e., Butry et al., 2001; Morton et al., 2003) are indicative of potential outcomes in boreal forests.

Fire processes are known to vary across longitudinal gradients in boreal Canada (Bonan and Shugart, 1989; Parisien and Sirois, 2003). Comparisons of fire processes across geographical areas typically involve estimates of fire attributes such as fire frequency, intensity, severity, extent, and season (Whelan, 1995; Reinhardt et al., 2001), of which fire frequency is the most prevalent. Boreal fire frequency has been estimated from historical fire records (i.e., Stocks et al., 2002) and through fire history studies (see review by Bergeron et al., 2004). Longitudinal variations in these estimates are particularly pronounced in east and west divisions of the Boreal Shield ecozone that divide Ontario (Fig. 1) where percent annual area burned over the 1959–1997 period calculated from the Canadian Large Fire Database (Stocks et al., 2002) was 0.6–0.8 and 0–0.2 in the west and east, respectively. Fire frequency estimated from fire history studies completed for small areas within these ecozone divisions (i.e., Suffling et al., 1982; Bergeron et al., 2001) indicated

that historical fire frequency in the BSE was less than one-third that of the BSW and current fire frequency in these areas estimated from the Canadian Large Fire Database suggest fire frequency in the BSE of Ontario is as little as one-tenth that of BSW (Bergeron et al., 2004).

Drought frequency has been identified as a factor controlling fire frequency in the eastern Boreal Shield (Bergeron and Archambault, 1993; Lefort et al., 2003; Girardin et al., 2004) and rainfall patterns associated with large-scale climate patterns are considered drivers of longitudinal variations in boreal fire frequency (Bonan and Shugart, 1989). Weather is a key influence on fire regimes (Whelan, 1995) and a primary determinant of fire incidence (Cunningham and Martell, 1973; Turner and Romme, 1994). Among conifer fuel types, weather is the most important factor influencing variation in fire behaviour and extreme fire weather results in fire behaviour that produces large and intense fires (Bessie and Johnson, 1995; Hély et al., 2001). In Canada, moisture level deficits sustained for just a few days or weeks can result in multiple ignitions of large fires (Johnson and Wowchuck, 1993; Skinner et al., 1999) and area burned is strongly influenced by long sequences of days with little or no precipitation (Flannigan and Harrington, 1988).

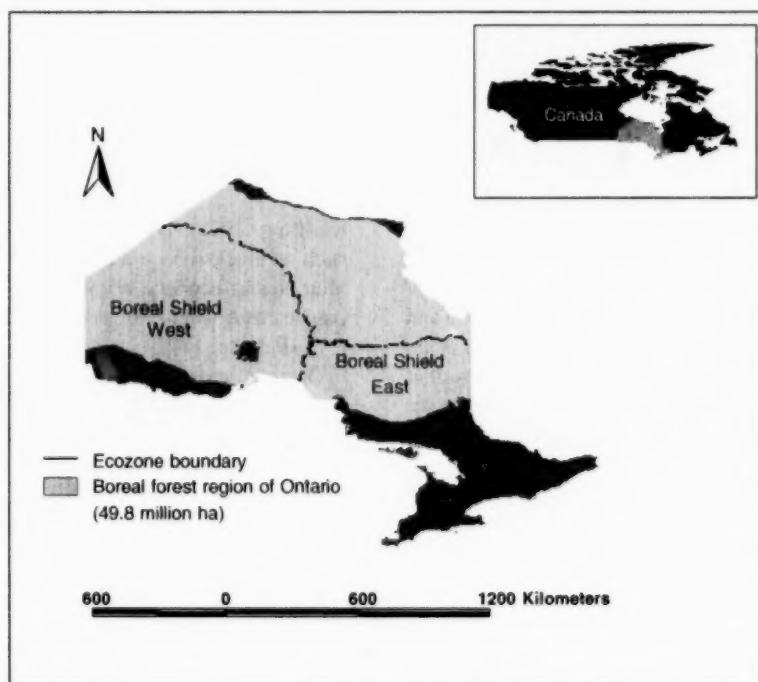


Fig. 1. Boreal forest region, and east and west divisions of the Boreal Shield ecozone, province of Ontario, Canada.

Variation in area burned has been explained by fire weather indices (Harrington et al., 1983; Flannigan and Wotton, 1991; Larsen and MacDonald, 1995; Larsen, 1996) and comparisons between area burned and mean fire season precipitation and temperature have produced significant correlations in western Canada (Larsen, 1996). Precipitation amount has little predictive capability (e.g., Flannigan and Harrington, 1988) since it is the pattern of rainfall throughout the fire season that influences fire ignition and behaviour rather than precipitation quantity (Turner, 1970).

Studies of fire and weather generally illustrate that weather variables explain a relatively small fraction of the variation in area burned. Flannigan and Harrington (1988) attribute this to complex processes that determine area burned in addition to weather, such as topography, fuel characteristics, season, latitude, and fire suppression policies and effectiveness. Across areas where these variables are broadly consistent, comparisons between fire and weather attributes are one means of providing insight into the nature of weather influences on fire processes.

While fire frequency is the most common fire attribute used to compare fire regimes, it provides little insight into the potential for extreme fire events that characterize boreal fire processes. Moritz (1997) introduced the statistics of extreme values described by Gaines and Denny (1993) as a method for characterizing extreme fire and fire weather events in a given area and time period. We used the statistics of extreme values to characterize fire size extremes in eastern and western divisions of the Boreal Shield ecozone in Ontario. We also characterize dry spell extremes, or runs of consecutive days with little or no rain, which are known to be a controlling factor on fire regimes in the Boreal Shield (i.e., Bergeron and Archambault, 1993; Lefort et al., 2003; Girardin et al., 2004). We used results of this analysis to investigate differences in the statistical characteristics of extreme fire and dry spell events between the eastern and western Boreal Shield and discuss the implications of our results for fire and land management in these areas.

2. Site descriptions and data

The Boreal Shield ecozone (Ecological Stratification Working Group, 1995) is dominated by conifer stands, with white and black spruce, balsam fir, and tamarack occurring as representative species. Climate is strongly continental with long cold winters and short warm summers. Study site boundaries for the analysis of fire size extremes were delineated within this ecozone to produce areas with internally

consistent forest fuels, ecoclimatic conditions, and fire suppression policy. Defined primarily by the Northern Coniferous and Northern Clay forest sections of the boreal forest region (Rowe, 1972), the sites are located in east and west divisions of the Boreal Shield ecozone described by Stocks et al. (2002) (Fig. 2) to reflect east–west disparities in climate and fire activity across the zone. Both study sites are bounded to the north by the limit of intensive fire suppression (Martell, 1994) and are within forest sections dominated by closed conifer forests (Rowe, 1972), which are most closely represented by the boreal spruce (C-2) and jack pine (C-3/4) fuel types of the Canadian Forest Fire Behaviour Prediction System (FBP) (Forestry Canada Fire Danger Group, 1992). The sites occupy different ecoclimatic regions with notably milder and moister conditions characteristic of the Northern Clay site, as compared with the Northern Coniferous (Table 1).

The Northern Coniferous site (51°23'N, 93°0'W) covers 1.7 million ha of the Lac Seul Upland ecoregion where black spruce is predominant, and associated with jack pine and tamarack on uplands and poorly drained lowlands, respectively. Frequent fires have favoured the spread of jack pine and representation of white birch over the ecoregion, which is covered by wetlands in 25% of its area. The Northern Clay site (48°32'N, 81°51'W) covers 984 694 ha of the Lake Timiscaming Lowland and Abitibi Plains ecoregions. Forests in this area are characterized by black spruce and balsam fir on wet sites, with jack pine dominating drier sites. Mixedwood stands of trembling aspen, balsam poplar, balsam fir, white spruce and black spruce are associated with improvements in drainage. There are relatively few lakes in this region with extensive areas of spruce–cedar swamp and poorly drained flats. Topography is level and there is an absence of surface rock.

Time series of the largest fire (ha) per year in each study site were compiled from a database of all reported fires in Ontario between 1976 and 1999 obtained from the Ontario Ministry of Natural Resources (Ontario Ministry of Natural Resources, 2001) (Fig. 2). On average, 43 fires burned 7911 ha per year over the 1976–1999 period in the Northern Coniferous site, compared with an annual average of 10 fires per year and 138 ha burned in the Northern Clay site. Fire frequency over the 1959–1999 period was estimated to be 0.462 and 0.046 percent annual area burned (Bergeron et al., 2004) in study areas near our Northern Coniferous and Northern Clay sites, respectively (Fig. 2, inset), which represent declines in fire frequency compared with historical conditions reported for these

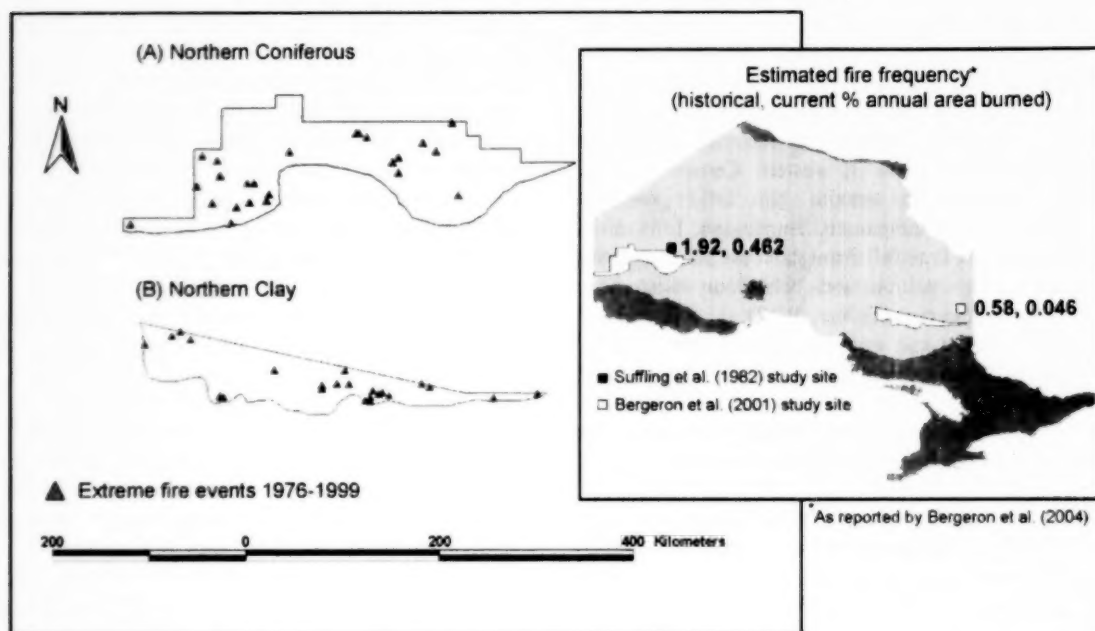


Fig. 2. Location of fire study sites. (A) Northern Coniferous, western Boreal Shield (BSW) and (B) Northern Clay, eastern Boreal Shield (BSE).

study areas (i.e., Suffling et al., 1982; Bergeron et al., 2001).

Daily fire weather recorded at 12:00 local standard time (temperature, wind speed, relative humidity, and precipitation for the previous 24 h), and Fire Weather Index System (Van Wagner, 1987) components calculated from these observations were obtained from the Ontario Ministry of Natural Resources for weather stations active over the 1963–1998 period (Ontario Ministry of Natural Resources, 1999) (Fig. 3). Time series of the maximum dry spell length per year were calculated for Dryden (49°47'N, 92°36'W) and Kapus-

kasing (49°24'N, 82°26'W) weather stations, which are located at equal latitudes in west and east divisions of the Boreal Shield ecozone, respectively (Fig. 3).

Droughts are generally measured as sequences of deficient precipitation below a predefined reference level (Sharma, 1998). We defined an extreme dry spell event as the longest run of consecutive days in a fire season (April–October) with <5 mm of precipitation in a 24 h period reported for a single weather station. Suitability of the “<5 mm” criterion was tested by comparing dry spell lengths associated with small and large size-classes of boreal forest fires that occurred in

Table 1
Climate conditions

	(A) Northern coniferous: Lac Seul Upland ecoregion ^a , Boreal Shield west (BSW) ecozone	(B) Northern clay: Lake Timiscaming Lowland and Abitibi Plains ecoregions ^a , Boreal Shield east (BSE) ecozone
Ecoclimatic region	Subhumid mid-boreal	Humid mid-boreal
Mean annual temperature (°C)	0.5	1–3
Mean summer temperature (°C)	14	14.5–15
Mean winter temperature (°C)	–14.5	–9–12
Range of mean annual precipitation across the area (mm)	450–700	750–1000

^a Ecological Stratification Working Group (1995).

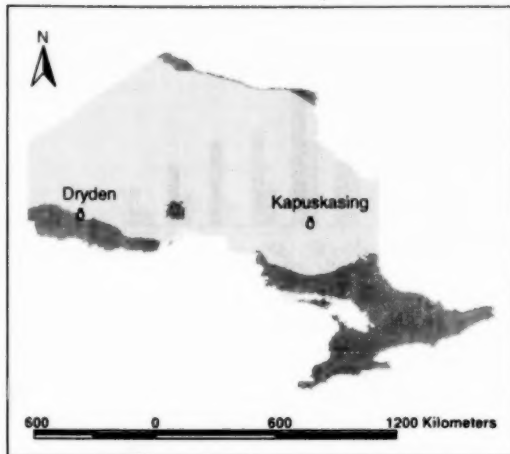


Fig. 3. Locations of Dryden and Kapuskasing fire weather stations used for the analysis of extreme dry spell events.

the intensive protection fire management zone of the Boreal the Shield ecozone of Ontario over the 1976–1999 period. Small fires consisted of a random sample of 100 fires ≤ 10 ha and all fires >4950 ha were classed as large fires. A Geographical Information System (GIS) was used to associate each fire with any concurrent dry spell recorded at the nearest weather station. We also investigated the timing of fires within the dry spell window by comparing dry spell length at time of fire discovery and dry spell length remaining at time of fire discovery, between small and large fires.

We compared the proportion of small and large fires that were associated with high or extreme fuel moisture conditions on the day of fire discovery and on the day of dry spell initiation to underline the complex relationship between fuel moisture conditions, dry spell events, and fire size. Fuel moisture conditions were represented by the Fine Fuel Moisture Code (FFMC) of the Canadian Fire Weather Index System (Van Wagner, 1987), which provides a relative rating of the moisture content in litter and other cured fine fuels. High or extreme FFMC values range from 87 to 101 in Ontario (Ontario Ministry of Natural Resources, 2002) and correspond to moisture contents $\leq 14\%$.

3. Methods

Detailed treatments of the statistics of extremes are found in Gumbel (1958) and Leadbetter et al. (1983). Meehl et al. (2000) provide a conceptual overview of the impact of changes in the mean, standard deviation, and variance on the frequency of extremes in weather variables. We used the methods outlined by Gaines and

Denny (1993) and Moritz (1997) to characterize the statistical properties of fire and dry spell observations in eastern and western divisions of the Boreal Shield ecozone of Ontario that are extreme relative to the rest of the population. The procedure involves recording the extreme value observed in each interval of a time series and ranking them in ascending order. A continuous probability function is fit to their cumulative distribution, $F(x)$, which defines the probability that the largest fire event or dry spell event in a year will be less than or equal to a given value of x :

$$F(x) = P(X_{\max} \leq x). \quad (1)$$

The inverse of $1 - F(x)$ is the return time, $T_r(x)$, which describes the expected number of years that will elapse between consecutive occurrences of the extreme value x :

$$T_r(x) = \frac{1}{1 - F(x)} \quad (2)$$

For large samples ($N \geq 20$) of extreme values that are independent and identically distributed, the cumulative probability function approaches an asymptotic form (Jacocks and Kneile, 1975):

$$F(x) = \exp\left(-\left[\frac{\alpha - \beta x}{\alpha - \beta \varepsilon}\right]^{1/\beta}\right), \quad (3)$$

where x is the maximum fire size or dry spell length, ε the most frequently occurring extreme value (mode), α measures the rate of increase of $F(x)$ with the natural logarithm of time, and the ratio α/β estimates the maximum fire or dry spell event achievable (when α and β are both >0).

For each time-series of extreme values, temporal independence was determined from lagged autocorrelations. Scatter plots of fire and weather extremes over time and Dickie–Fuller tests for the presence of unit roots were used to investigate stationarity. Moritz (1997) describes conditions necessary for producing a useful characterization of fire extremes from maximum fire size data: (1) maximum fire sizes in the time series must be large relative to the population, such that they account for the majority of the area burned and (2) single large fires can not burn the majority of the study area, which would create spatial dependence. Percent area burned by extreme fire events in a year and over the study period, and percent of the study area burned by individual fires were used to assess the appropriateness of the fire data. Maximum likelihood estimates of ε , α , and β were obtained with the SAS NLIN procedure (SAS Institute, 1999) by maximizing the logarithm of

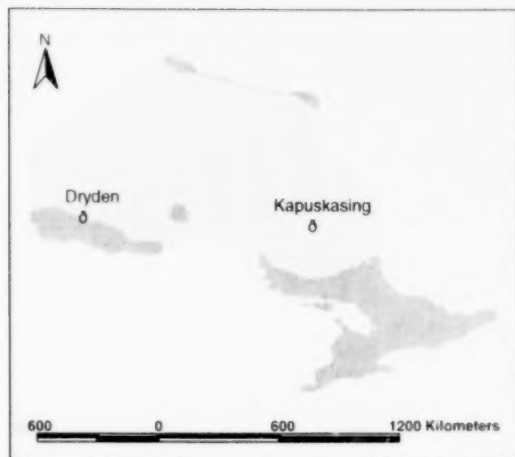


Fig. 3. Locations of Dryden and Kapuskasing fire weather stations used for the analysis of extreme dry spell events.

the intensive protection fire management zone of the Boreal the Shield ecozone of Ontario over the 1976–1999 period. Small fires consisted of a random sample of 100 fires ≤ 10 ha and all fires >4950 ha were classed as large fires. A Geographical Information System (GIS) was used to associate each fire with any concurrent dry spell recorded at the nearest weather station. We also investigated the timing of fires within the dry spell window by comparing dry spell length at time of fire discovery and dry spell length remaining at time of fire discovery, between small and large fires.

We compared the proportion of small and large fires that were associated with high or extreme fuel moisture conditions on the day of fire discovery and on the day of dry spell initiation to underline the complex relationship between fuel moisture conditions, dry spell events, and fire size. Fuel moisture conditions were represented by the Fine Fuel Moisture Code (FFMC) of the Canadian Fire Weather Index System (Van Wagner, 1987), which provides a relative rating of the moisture content in litter and other cured fine fuels. High or extreme FFMC values range from 87 to 101 in Ontario (Ontario Ministry of Natural Resources, 2002) and correspond to moisture contents $\leq 14\%$.

3. Methods

Detailed treatments of the statistics of extremes are found in Gumbel (1958) and Leadbetter et al. (1983). Meehl et al. (2000) provide a conceptual overview of the impact of changes in the mean, standard deviation, and variance on the frequency of extremes in weather variables. We used the methods outlined by Gaines and

Denny (1993) and Moritz (1997) to characterize the statistical properties of fire and dry spell observations in eastern and western divisions of the Boreal Shield ecozone of Ontario that are extreme relative to the rest of the population. The procedure involves recording the extreme value observed in each interval of a time series and ranking them in ascending order. A continuous probability function is fit to their cumulative distribution, $F(x)$, which defines the probability that the largest fire event or dry spell event in a year will be less than or equal to a given value of x :

$$F(x) = P(X_{\max} \leq x). \quad (1)$$

The inverse of $1 - F(x)$ is the return time, $T_r(x)$, which describes the expected number of years that will elapse between consecutive occurrences of the extreme value x :

$$T_r(x) = \frac{1}{1 - F(x)} \quad (2)$$

For large samples ($N \geq 20$) of extreme values that are independent and identically distributed, the cumulative probability function approaches an asymptotic form (Jacocks and Kneile, 1975):

$$F(x) = \exp\left(-\left[\frac{\alpha - \beta x}{\alpha - \beta c}\right]^{1/\beta}\right), \quad (3)$$

where x is the maximum fire size or dry spell length, c the most frequently occurring extreme value (mode), α measures the rate of increase of $F(x)$ with the natural logarithm of time, and the ratio α/β estimates the maximum fire or dry spell event achievable (when α and β are both >0).

For each time-series of extreme values, temporal independence was determined from lagged autocorrelations. Scatter plots of fire and weather extremes over time and Dickie–Fuller tests for the presence of unit roots were used to investigate stationarity. Moritz (1997) describes conditions necessary for producing a useful characterization of fire extremes from maximum fire size data: (1) maximum fire sizes in the time series must be large relative to the population, such that they account for the majority of the area burned and (2) single large fires can not burn the majority of the study area, which would create spatial dependence. Percent area burned by extreme fire events in a year and over the study period, and percent of the study area burned by individual fires were used to assess the appropriateness of the fire data. Maximum likelihood estimates of c , α , and β were obtained with the SAS NLIN procedure (SAS Institute, 1999) by maximizing the logarithm of

the likelihood function (see Appendix of Gaines and Denny, 1993). Differences in fire extremes in the Northern Clay and Northern coniferous sites and dry spell extremes at the Dryden and Kapuskasing weather stations were investigated by using a Kolmogorov–Smirnov test to compare the empirical cumulative probability distributions. Maximum likelihood parameter estimates were compared with *t*-tests using standard errors produced by the NLIN procedure and Bonferroni corrections to control for the false positive rate that can result from multiple comparisons.

4. Results

Comparisons between dry spell event lengths associated with small (i.e., ≤ 10 ha) and large (i.e., >4950 ha) size-classes of boreal forest fires that occurred over the 1976–1999 period indicated that dry spell events >15 days in length were associated with 76% of large fires compared with only 33% of small fires (Fig. 4). Dry spell lengths associated with large fires were significantly longer, both overall and at the time of fire discovery, compared with those associated with small fires (Table 2). Dry spell length remaining at the time of time of fire discovery was also significantly longer for large fires, as compared with small fires (Table 2). The proportion of large fires occurring during dry spells that were initiated under high or extreme fuel moisture conditions was significantly higher as compared to small fires, and a significantly higher proportion of large fires occurred on days with high or extreme fuel moisture conditions (Table 3). These results demonstrate the influence of

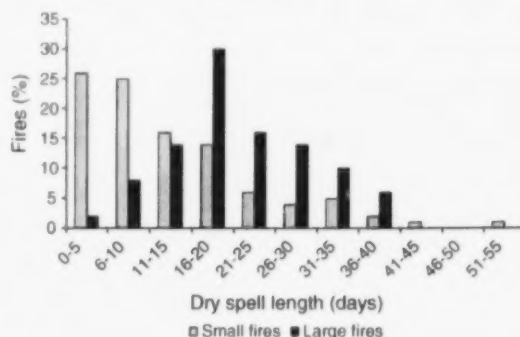


Fig. 4. Percent of boreal forest fires by dry spell class in the intensive protection fire management zone of the Boreal Shield ecozone during the 1976–1999 period. Small fires consist of a random sample of 100 fires ≤ 10 ha. Large fires are all fires >4950 ha.

fuel moisture conditions and the timing of ignition on the relationship between fire size and dry spell length.

Autocorrelation coefficients calculated for each time series were not significantly different from zero at the 95% confidence limit, indicating temporal independence. Scatter plots of fire and weather extremes over time (Fig. 5) and Dickie–Fuller tests for the presence of unit roots indicated that all four time-series are stationary. Maximum fire sizes contained in Northern Coniferous and Northern Clay time series each burned $<5\%$ of the total study area. The number of years in which the largest fire accounted for at least one half of the total area burned that year was 71% for the Northern Clay and 67% for the Northern Coniferous. Total area burned contained in the time series of extreme fire events was 89% for the Northern Coniferous and 85%

Table 2

(A) Dry spell length, (B) dry spell length at the time of fire discovery, and (C) dry spell length remaining at the time of fire discovery, associated with large boreal forest fires (>4950 ha) and a random sample of small boreal forest fires (≤ 10 ha) in the intensive protection fire management zone, Boreal Shield ecozone of Ontario (1976–1999)

	(A) Dry spell length		(B) Dry spell length at time of fire discovery		(C) Dry spell length remaining at time of fire discovery	
	Small fires	Large fires	Small fires	Large fires	Small fires	Large fires
N	100	50	100	50	100	50
Mean	12.91 ^a	21.52 ^a	7.99 ^b	15.24 ^b	4.92 ^c	7.28 ^c
Median	10	20	5	12.5	4	6
Mode	8	20	1	8	0	5
S.D.	10.85	8.15	8.36	7.33	5.1	4.78
Kurtosis	1.12	-0.55	1.08	-1.02	1.23	-0.01
Skewness	1.11	0.29	1.32	0.25	1.8	0.82
Minimum	0	5	0	1	0	0
Maximum	52	38	36	28	26	21

^a Significantly different between small and large fires (Wilcoxon rank sum test, $p < 0.0001$).

^b Significantly different between small and large fires (Wilcoxon rank sum test, $p < 0.0001$).

^c Significantly different between small and large fires (Wilcoxon rank sum test, $p < 0.001$).

Table 3

Proportion of boreal forest fires in the intensive protection fire management zone, Boreal Shield ecozone of Ontario (1976–1999), that were associated with fuel moisture conditions in the high or extreme range of the Fine Fuel Moisture Code (FFMC) on the day of (A) dry spell initiation and (B) fire discovery

	<i>N</i> ^a	(A) Conditions on the day of dry spell event initiation	<i>N</i>	(B) Conditions on the day of fire discovery
Small fires (<10 ha)	88	0.05 ^b	100	0.30 ^c
Large fires (>4950 ha)	50	0.22 ^b	50	0.86 ^c

High or extreme FFMC values range from 87 to 101 in Ontario (Ontario Ministry of Natural Resources, 2002) and correspond to moisture contents $\leq 14\%$.

^a Excluding small fires associated with a dry spell length of 0 (i.e., occurred on a day with >5 mm precipitation).

^b Significantly different between small and large fires (χ^2 , 1 d.f. = 10.03, $p = 0.0015$).

^c Significantly different between small and large fires (χ^2 , 1 d.f. = 41.843, $p < 0.0001$).

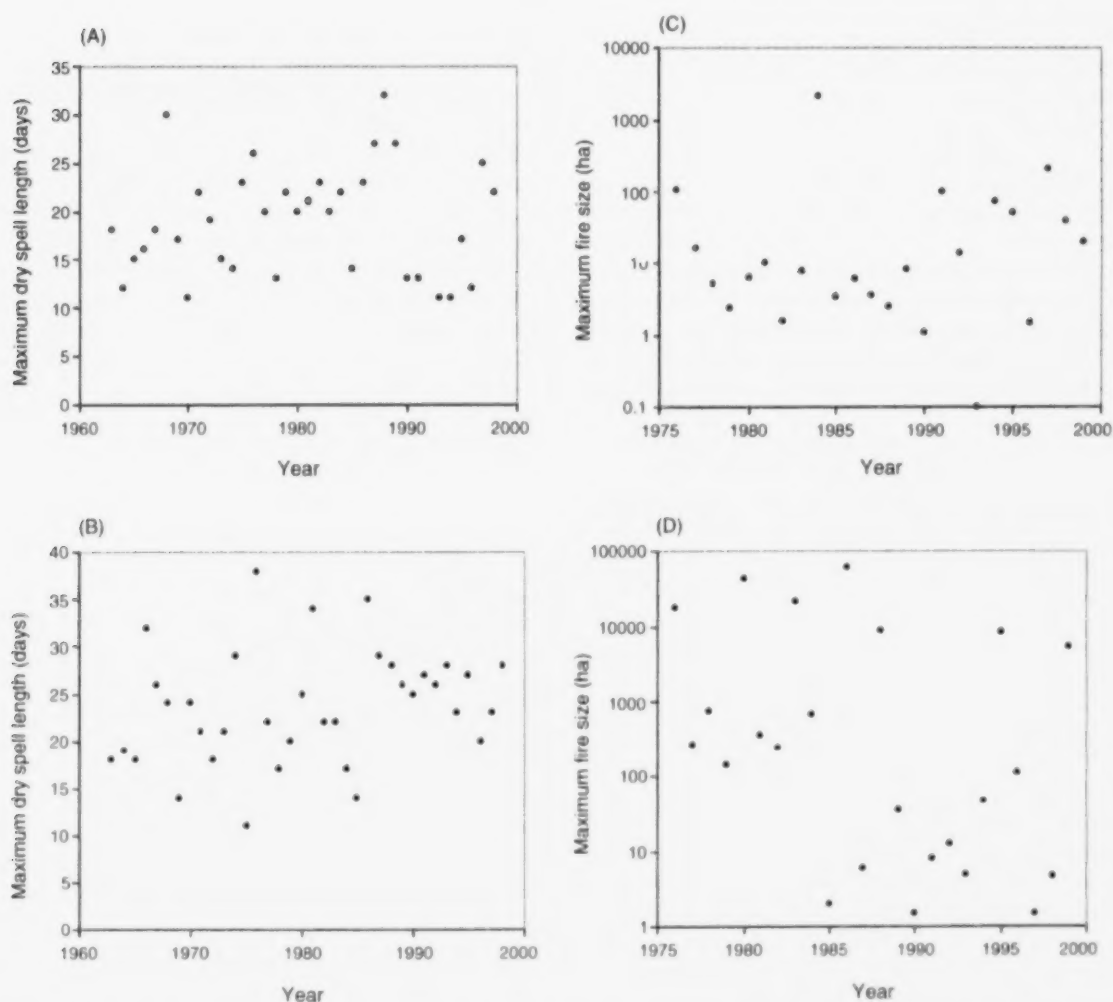


Fig. 5. Scatter plots of maximum dry spell lengths over time recorded at (A) Kapuskasing and (B) Dryden weather stations; maximum fire sizes over time in (C) Northern Clay and (D) Northern Coniferous study sites.

Table 4

Maximum likelihood estimates of model parameters calculated for (A) Northern Coniferous and Northern Clay study sites; (B) Dryden and Kapuskasing weather stations

Parameter	(A) Maximum likelihood estimates, extreme fire event distributions (1976–1999)		(B) Maximum likelihood estimates, extreme dry spell event distributions (1963–1998)	
	Boreal Shield West Northern Coniferous	Boreal Shield East Northern Clay	Boreal Shield West Dryden	Boreal Shield East Kapuskasing
α	-0.9607	-0.2862	11.856	10.051
β	-3.733 ^a	-1.7054 ^a	0.281	0.244
ε	32.092 ^b	4.7014 ^b	21.075 ^c	16.122 ^c
S.E. of α	2.599	0.4056	1.029	1.021
S.E. of β	0.201	0.0859	0.043	0.054
S.E. of ε	4.199	0.1638	0.086	0.114

^a Parameters significantly different from each other at the 99% confidence level.

^b Parameters significantly different from each other at the 99% confidence level.

^c Parameters significantly different from each other at the 99% confidence level.

for the Northern Clay, which suggests it is reasonable to use the statistics of extremes to characterize the fire regimes of our study areas. The fitted distribution of extreme values (Eq. (3)) using maximum likelihood estimation resulted in excellent fits for all datasets. Coefficients of determination (R^2) for all models were ≥ 0.98 .

Kolmogorov–Smirnov test statistics indicated significant differences in the cumulative probability distributions of extreme fire events in Northern Coniferous and Northern Clay sites, Boreal Shield west (BSW) and east (BSE), respectively. Comparison

of maximum likelihood estimates for each study area using *t*-tests with Bonferroni corrections resulted in significant differences for two of three parameters (Table 4). There were differences in parameter β and parameter ε , which indicates a significant shift in the position of the distribution (Fig. 6) and a decline in the modal fire size from 32.1 ha in BSW to 4.7 ha in BSE. The return time of a 10 000 ha fire was 5.2 years in BSW compared with 91.8 years in BSE. The gap in the distribution of fire sizes between 700 and 5000 ha in the Northern Coniferous site may indicate that the study size is not ideal.

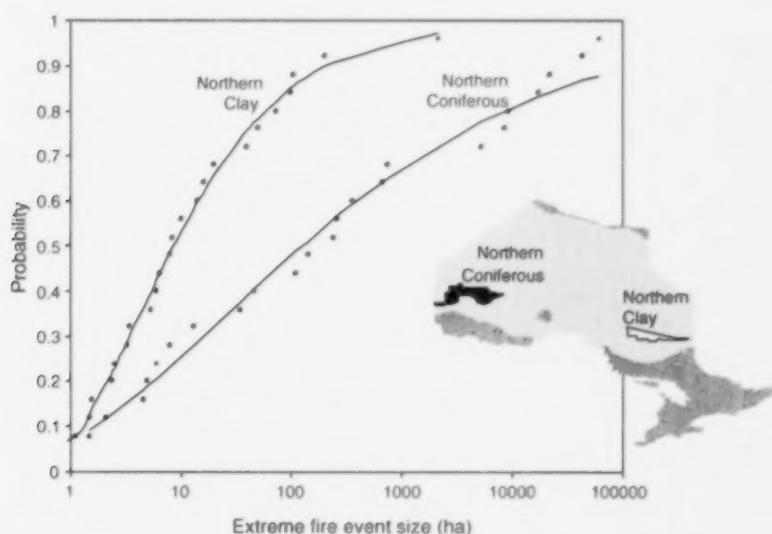


Fig. 6. Cumulative probabilities for maximum fire sizes Northern Coniferous and Northern Clay study sites, west and east Boreal Shield respectively (describes the chance that the largest fire in a year will be less than or equal to a given value of x). Solid line curves are maximum likelihood fits of continuous probability functions.

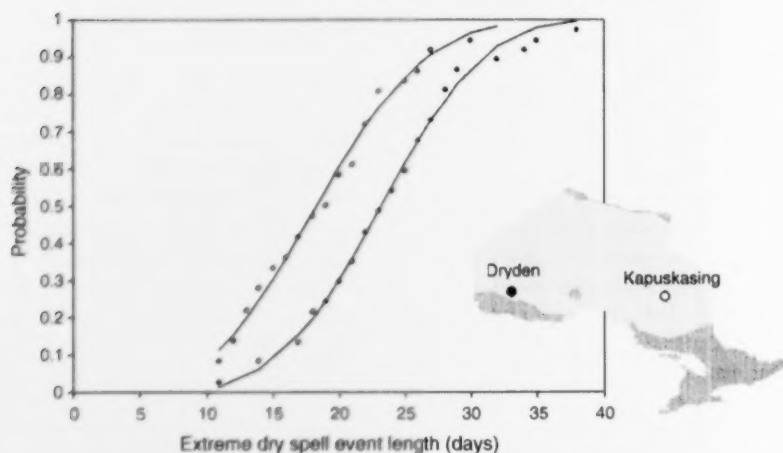


Fig. 7. Cumulative probabilities for maximum dry spell lengths for Dryden and Kapuskasing weather stations, west and east Boreal Shield, respectively (describes the chance that the longest dry spell in a year will be less than or equal to a given value of x). Solid line curves are maximum likelihood fits of continuous probability functions.

Kolmogorov–Smirnov test statistics for comparisons between Dryden (BSW) and Kapuskasing (BSE) weather stations indicated that cumulative probability distributions of extreme dry spell events were significantly different. Comparisons of maximum likelihood estimates for each weather station using t -tests with a Bonferroni correction indicated significant differences for parameter ϵ (Table 4), which corresponds to a modal dry spell event length of 21.1 days in BSW compared with 16.1 days in BSE (Fig. 7). The return time of a 30 days dry spell event was 7.5 years in BSW compared with 27.8 years in BSE.

5. Discussion and conclusion

Results confirm existing evidence that fire processes in boreal forest ecosystems differ dramatically between east (BSE) and west (BSW) divisions of the Boreal Shield ecozone in Ontario. Large fires occur more frequently in the BSW, which is consistent with fire history studies in these areas that indicate fire frequency in the BSE is as little as one-tenth that of BSW (Bergeron et al., 2004). Analysis of dry spell extremes in these areas indicate that long dry spells also occur more frequently in the BSW, as compared with the BSE. These results are consistent with previous studies that suggest drought frequency has been a controlling mechanism on fire regimes in the eastern Boreal Shield (i.e., Bergeron and Archambault, 1993; Lefort et al., 2003; Girardin et al., 2004).

Analysis of dry spell lengths associated with small and large fire size-classes confirmed that large fires are

consistently associated with dry spells, however, the relationship between fire size and dry spell length is complex and will depend on initial fuel moisture conditions at the start of the dry spell and the timing of a fire ignition within the dry spell window. Long dry spells will not necessarily be associated with large fires, if for example the dry spell begins when fuel moisture is elevated and fire ignitions occur early within the dry spell window, or not at all. Our analysis of dry spell extremes provides a general characterization of dry spell patterns in an area that can be used to assess the probability of these extreme events. By assessing dry spell extremes independently of other factors, this information can be combined with available data on ignition probabilities and fuel moisture conditions at a given point in time to investigate overall risk factors associated with extreme fire events.

Most fire and land management agencies recognize that fire cannot and should not be excluded from the boreal forest and efforts are made to accommodate natural fire processes in boreal wilderness areas, such as Wabakimi Provincial Park in Ontario (Beverly and Martell, 2003). The decision to allow a fire to burn occurs under uncertain, long-term future weather conditions and efforts have been made to characterize the likelihood of relevant weather events. For example, Redmond et al. (1983) calculated the probability of receiving appreciable amounts of precipitation within specific time intervals following a fire ignition and Latham and Rothermel (1993) presented a methodology for estimating fire stopping precipitation events that could be used by managers to determine when

precipitation might be expected to stop an ongoing fire. In contrast to these methods, which characterize typical precipitation patterns in an area, our analysis of dry spell extremes provides insight into the risk of extremely long intervals without appreciable amounts of precipitation.

Characterization of fire extremes is also relevant to fire management in wilderness areas. Fire processes in a wilderness area can be characterized in terms of the historical average annual percent burned, but this will not indicate the likelihood that a single fire will burn some large portion of that area. Theories on reserve design suggest that parks created to accommodate natural disturbance processes must be large relative to the maximum potential disturbance size (Pickett and Thompson, 1978; Baker, 1992). Knowledge of fire extremes may indicate areas of the landscape where natural processes can or cannot be accommodated given the sizes of existing protected areas, or those areas of the landscape where protected areas would have to be created or expanded in order to accommodate fire processes, given habitat and conservation objectives.

Unlike fire frequency estimates, our analysis of fire extremes provides a characterization of fire processes relevant to the attributes of individual fires. In commercial forest areas, estimates of the risk of large fire events is important for timber supply modeling and for the analysis of vulnerabilities associated with forest based communities, such as the likelihood of a mill-ending fire event in an area. As a complement to other fire regime attributes, characterization of fire and weather extremes can be used to develop realistic models of fire processes in the Boreal Shield ecozone of Ontario.

Given fire management objectives that include supporting specified levels of fire activity in some areas of the landscape, and the potential for increased fire activity associated with future climate change (Flannigan et al., 1998; Stocks et al., 1998; Wotton et al., 2003), there is a need to characterize extreme fire and weather events to quantify the risks associated with these extreme events and the interactions between them and those factors that may influence them now and in the future. It is generally accepted that there have been increases in both global mean temperature and global precipitation since the start of the 20th century (Nicholls et al., 1996). Climate model simulations consistently suggest increases in global precipitation for mid- and high-latitudes under global warming scenarios (Schar et al., 1996; Hennessy et al., 1997). These increases in temperature and precipitation are expected to result in increasing incidence of extreme events (Mearns et al.,

1984; Easterling et al., 2000) as well as intensification of the earth's hydrological cycle (Idso and Balling, 1991). Trenberth (1999) predicted the intensification of droughts and rainfall events as a result of climate change induced temperature increases that increase the water-holding capacity of the atmosphere. Our assessment of fire and dry spell extremes may provide a useful baseline for assessing future climate change impacts on fire regimes in the Boreal Shield ecozone of Ontario.

This paper outlines a very preliminary, exploratory assessment of fire and weather extremes in the Boreal Shield. The statistical properties of extreme fire and dry spell events described here may be of practical use for assessments of general risks associated with permitting an individual fire to burn in Northern Clay and Northern Coniferous forest sections within the Boreal Shield ecozone and for identifying the potential impacts of climate change on Boreal Shield fire regimes. Applications of the statistics of extreme values for investigating natural processes such as weather have become increasingly common in recent years in response to concerns over potential climate change impacts and new methodologies and approaches continue to be developed. Future research should focus on emerging methodologies for analyzing variations in fire and weather extremes across Ontario and elsewhere in Canada. Analysis of joint distributions of fire and weather variables could provide additional insight into fire processes in the Boreal Shield and further study on the impact of time series length and study size on the analysis of boreal fire extremes is suggested.

Acknowledgements

This research was supported by the Ontario Graduate Scholarship Program, the Natural Sciences and Engineering Research Council of Canada, and the University of Toronto. We thank B. Stocks (Canadian Forest Service), D. Balsillie (University of Toronto), R. Suffling (University of Waterloo), M.-J. Fortin (University of Toronto), and S. Kant (University of Toronto), for providing helpful comments on the manuscript. Comments from two anonymous reviewers prompted significant improvements in the presentation of results.

References

- Alberta Sustainable Resource Development, 2001. Final Documentation Report Chisolm Fire (LWF-063). Edmonton.
- Attiwill, P.M., 1994. The disturbance of forest ecosystems: the ecological basis for conservative management. *Forest Ecol. Manage.* 63, 247–300.

- Baker, W.L., 1992. The landscape ecology of large disturbances in the design and management of nature reserves. *Landsc. Ecol.* 7, 181–194.
- Bergeron, Y., 1991. The influence of island and mainland lakeshore landscape on boreal forest fire regimes. *Ecology* 72, 1980–1992.
- Bergeron, Y., Archambault, S., 1993. Decreasing frequency of forest fires in the southern boreal zone of Quebec and its relation to global warming since the end of the 'Little Ice Age'. *The Holocene* 3, 255–259.
- Bergeron, Y., Flannigan, M., Gauthier, S., Leduc, A., Lefort, P., 2004. Past, current and future fire frequency in the Canadian boreal forest: implications for sustainable forest management. *Ambio* 33, 356–360.
- Bergeron, Y., Gauthier, S., Kafka, V., Lefort, P., Lesieur, D., 2001. Natural fire frequency for the eastern boreal forest: consequences for sustainable forestry. *Can. J. Forest Res.* 31, 384–391.
- Bessie, W.C., Johnson, E.A., 1995. The relative importance of fuels and weather on fire behavior in subalpine forests. *Ecology* 76, 747–762.
- Beverly, J.L., Martell, D.L., 2003. Characterizing historical variability in boreal fire frequencies: Implications for fire and forest management. In: Arthaud, G.J., Barrett, T.M. (Eds.), *Proceedings of the Eighth Symposium on Systems Analysis in Forest Resources*, Snowmass Village, Colorado, USA, September 27–30. Kluwer Academic Publishers, Boston, pp. 3–14.
- Bonan, G.B., Shugart, H.H., 1989. Environmental factors and ecological processes in boreal forests. *Annu. Rev. Ecol. Systemat.* 20, 1–28.
- Butry, D.T., Mercer, D.E., Prestmon, J.P., Pye, J.M., Holmes, T.P., 2001. What is the price of a catastrophic wildfire? *J. Forestry* 99 (11), 9–17.
- Cunningham, A.A., Martell, D.L., 1973. A stochastic model for the occurrence of man-caused forest fires. *Can. J. Forest Res.* 3, 282–287.
- Easterling, D.R., Meehl, G.A., Parmesan, C., Changnon, S.A., Karl, T.R., Mearns, L.O., 2000. Climate extremes: observations, modeling, and impacts. *Science* (Washington, DC) 289, 2068–2074.
- Ecological Stratification Working Group, 1995. *A National Ecological Framework for Canada*. Agriculture and Agri-Food Canada and Environment Canada, Ottawa.
- Flannigan, M., Bergeron, Y., Englemark, O., Wotton, M., 1998. Future wildfire in circumboreal forests in relation to global warming. *J. Vegetat. Sci.* 9, 469–476.
- Flannigan, M.D., Harrington, J.B., 1988. A study of the relation of meteorological variables to monthly provincial area burned by wildfire in Canada (1953–1980). *J. Appl. Meteorol.* 27, 441–452.
- Flannigan, M.D., Wotton, B.M., 1991. Lightning-ignited forest fires in northwestern Ontario. *Can. J. Forest Res.* 21, 277–287.
- Forestry Canada Fire Danger Group, 1992. Development and structure of the Canadian Forest Fire Behavior Prediction System. Forestry Canada Information Report ST-X-3.
- Gaines, S.D., Denny, M.W., 1993. The largest, smallest, highest, lowest, longest, and shortest: extremes in ecology. *Ecology* 74, 1677–1692.
- Girardin, M.-P., Tardiff, J., Flannigan, M.D., Wotton, B.M., Bergeron, Y., 2004. Trends and periodicities in the Canadian Drought Code and their relationships with atmospheric circulation for the southern Canadian boreal forest. *Can. J. Forest Res.* 34, 103–119.
- Gumbel, E.J., 1958. *Statistics of Extremes*. Columbia University Press, New York.
- Harrington, J.B., Flannigan, M.D., Van Wagner, C.E., 1983. A study of the relation of components of the Fire Weather Index to monthly provincial area burned by wildfire in Canada 1953–1980. *Peta-wawa National Forestry Institute, Information Report PI-X-25*, Chalk River, Ontario.
- Heinselman, M.L., 1971. The natural role of fire in the northern conifer forests. In: Slaughter, C.W., Barney, R.J., Hansen, G.M. (Eds.), *Proceedings, Fire in the northern environment*, University of Alaska College, Fairbanks, Alaska, April 13–14. USDA For. Serv., Pacific Northwest Forest and Range Experiment Station, Portland, OR, pp. 64–72.
- Hély, C., Flannigan, M., Bergeron, Y., McRae, D., 2001. Role of vegetation and weather on fire behaviour in the Canadian mixed-wood boreal forest using two fire behaviour prediction systems. *Can. J. Forest Res.* 31, 430–441.
- Hennessy, K.J., Gregory, J.M., Mitchell, J.F.B., 1997. Changes in daily precipitation under enhanced greenhouse conditions. *Climate Dynam.* 13, 667–680.
- Idso, S.B., Balling, R.C., 1991. Recent trends in United States precipitation. *Environ. Conserv.* 18, 71–73.
- Jacobs, J.L., Kneile, K.R., 1975. Statistical prediction of maximum time-variant inlet distortion levels. *Arnold Engineering Development Center Technical Report AD/A-004*. U.S. Department of Commerce, National Technical Information Service, Washington, DC.
- Johnson, E.A., 1992. *Fire and Vegetation Dynamics: Studies from the North American Boreal Forest*. Cambridge University Press, Cambridge.
- Johnson, E.A., Wowchuck, D.R., 1993. Wildfires in the southern Canadian Rocky Mountains and their relationship to mid-tropospheric anomalies. *Can. J. Forest Res.* 23, 1213–1222.
- Larsen, C.P.S., 1996. Fire and climate dynamics in the boreal forest of northern Alberta, Canada from AD 1850–1989. *Holocene* 6, 449–456.
- Larsen, C.P.S., 1997. Spatial and temporal variations in boreal forest fire frequency in northern Alberta. *J. Biogeogr.* 24, 663–673.
- Larsen, C.P.S., MacDonald, G.M., 1995. Relations between tree-ring widths, climate, and annual area burned in the boreal forest of Alberta. *Can. J. Forest Res.* 25, 1746–1755.
- Latham, D.J., Rothermel, R.C., 1993. Probability of fire-stopping precipitation events. *USDA Forest Service, Research Note INT-410*.
- Leadbetter, M.R., Lindgren, G., Rootzen, H., 1983. *Extremes and Related Properties of Random Sequences and Processes*. Springer-Verlag, New York.
- Lefort, P., Gauthier, S., Bergeron, Y., 2003. The influence of fire weather and land use on the fire regime of the Lake Abitibi area, eastern Canada. *Forest Sci.* 49, 509–521.
- Martell, D.L., 1994. The impact of fire on timber supply in Ontario. *Forestry Chronicle* 70, 164–173.
- Mearns, L.O., Katz, R.W., Schneider, S.H., 1984. Extreme high-temperature events: Changes in their probabilities with changes in mean temperature. *J. Appl. Meteorol.* 23, 1601–1613.
- Meehl, G.A., Karl, T., Easterling, D.R., Changnon, S., 2000. An introduction to trends in extreme weather and climate events: observations, socioeconomic impacts, terrestrial ecological impacts, and model projections. *Bull. Am. Meteorol. Soc.* 81, 413–416.
- Moritz, M.A., 1997. Analyzing extreme disturbance events: fire in Los Padres National Forest. *Ecol. Appl.* 7, 1252–1262.
- Morton, D.C., Roessing, M.E., Camp, A.E., Tyrell, M.L., 2003. *Assessing the Environmental, Social, and Economic Impacts of Wildfire*. Yale University Global Institute of Sustainable Forestry Research Paper 001, New Haven, Connecticut.
- Nicholls, N., Gruza, G.V., Jouzel, J., et al., 1996. Observed climate variability and change. In: Houghton, J.T., et al. (Eds.), *Climate*

- Change the Science of Climate Change. Cambridge University Press, Cambridge, pp. 132–192.
- Ontario Ministry of Natural Resources, 1999. Weather database. Unpublished manuscript. Aviation and Forest Fire Management Branch, 70 Foster Dr., Suite 400, Sault Ste. Marie, Ont., P6A 6V5.
- Ontario Ministry of Natural Resources, 2001. Fire database. Unpublished manuscript. Aviation and Forest Fire Management Branch, 70 Foster Dr., Suite 400, Sault Ste. Marie, Ont., P6A 6V5.
- Ontario Ministry of Natural Resources, 2002. Initial Attack Fire Boss Course. Aviation and Forest Fire Management Branch Sault Ste. Marie, Ontario.
- Parisien, M.-A., Sirois, L., 2003. Distribution and dynamics of tree species across a fire frequency gradient in the James Bay region of Quebec. *Can. J. Forest Res.* 33, 243–256.
- Payette, S., 1992. Fire as a controlling process in the North American boreal forest. In: Shugart, H.H., Leemans, R., Bonan, G.B. (Eds.) *A Systems Analysis of the Global Boreal Forest*. Cambridge University Press, Cambridge, pp. 144–169.
- Pickett, S.T.A., Thompson, J.N., 1978. Patch dynamics and the design of nature reserves. *Biol. Conserv.* 13, 27–37.
- Redmond, K.T., Deeming, J.E., Murphy, A.H., 1983. An analysis of daily precipitation data to support management decisions regarding wilderness fires. In: *Proceedings of the Eighth Conference on Probability and Statistics in Atmospheric Sciences*. Hot Springs, Arizona, pp. 83–87.
- Reinhardt, E.D., Keane, R.E., Brown, J.K., 2001. Modeling fire effects. *Int. J. Wildl. Fire* 10, 373–380.
- Rowe, J.S., 1972. *Forest Regions of Canada*. Canadian Forest Service Publication 1300, Ottawa.
- SAS Institute, 1999. *SAS/STAT User's Guide*, Version 8. SAS Institute, Cary, NC.
- Schar, C., Frei, C., Luthi, D., Davies, H.C., 1996. Surrogate climate change scenarios for regional climate models. *Geophys. Res. Lett.* 23, 669–672.
- Sharma, T.C., 1998. An analysis of non-normal Markovian extremal droughts. *Hydrol. Process.* 12, 597–611.
- Skinner, W.R., Stocks, B.J., Martell, D.L., Bonsal, B., Shabbar, A., 1999. The association between circulation anomalies in the mid-troposphere and area burned by wildland fire in Canada. *Theor. Appl. Climatol.* 63, 89–105.
- Stocks, B.J., Fosberg, M.A., Lynham, T.J., Mearns, L., Wotton, B.M., Yang, Q., Jin, J.Z., Lawrence, K., Hartley, G.R., Mason, J.A., McKenney, D.W., 1998. Climate change and forest fire potential in Russian and Canadian boreal forests. *Climat. Change* 38, 1–13.
- Stocks, B.J., Mason, J.A., Todd, J.B., Bosch, E.M., Wotton, B.M., Amiro, B.D., Flannigan, M.D., Hirsch, K.G., Logan, K.A., Martell, D.L., Skinner, W.R., 2002. Large forest fires in Canada, 1959–1997. *J. Geophys. Res.* 108 (D1) Art. No. 8149.
- Suffling, R., 1990. Wildland fire management and landscape diversity in the boreal forest of northwestern Ontario during an era of climatic warming. In: Nodvin, S.C. (Ed.), *Proceedings of the Fire and the Environment: Ecological and Cultural Perspectives*. Knoxville, Tennessee, March 20–24. USDA For. Serv. Gen. Tech. Rep. SE-69, pp. 97–106.
- Suffling, R., Smith, B., Molin, J.D., 1982. Estimating past forest age distributions and disturbance rates in North-western Ontario. *J. Environ. Manage.* 45–56.
- Trenberth, K.E., 1999. Conceptual framework for changes of extremes of the hydrological cycle with climate change. *Climat. Change* 42, 327–339.
- Turner, J.A., 1970. Hours of sunshine and fire season severity over the Vancouver Forest District. *Forestry Chronicle* 46, 106–111.
- Turner, M.G., Romme, W.H., 1994. Landscape dynamics in crown fire ecosystems. *Landsc. Ecol.* 9, 59–77.
- Van Wagner, C.E., 1987. *Development and Structure of the Canadian Forest Fire Weather Index System*. Canadian Forestry Service, Forestry Technical Report 35, Ottawa.
- Weir, J.M.H., Johnson, E.A., Miyanishi, K., 2000. Fire frequency and the spatial age mosaic of the mixed-wood boreal forest in western Canada. *Ecol. Appl.* 10, 1162–1177.
- Whelan, R.J., 1995. *The Ecology of Fire*. Cambridge University Press, New York.
- Wotton, B.M., Martell, D.L., Logan, K.A., 2003. Climate change and people-caused forest fire occurrence in Ontario. *Climat. Change* 60, 275–295.

